Thrust 3: Electrical Characterization Overview

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Outline

- Overview-Electrical Characterization
- Device Modification/Defect Generation
- Characterization
- Related Results and Preliminary Models

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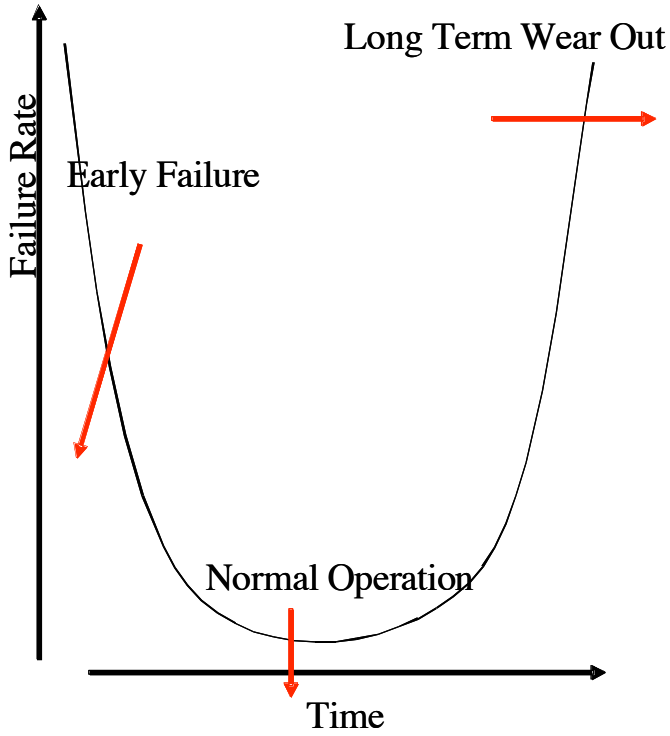
Overview

- Tightly integrated approach
  - Test structure fabrication
  - Materials characterization
  - Electro(thermo)(opto)(mechano) characterization
    - Device modification/Defect generation
      - Electrical (DC and RF), mechanical, thermal, optical stresses
    - Characterization
  - Modeling
  - Statistics

Overview

- Goal
  - Employ multiple characterization vectors
  - Gain insight into physical degradation mechanisms
  - Feedback into predictive models
  - Compare predictions with characterization results
    - Collect sufficient statistics for confidence
    - Design high performance and high reliability compound semiconductor electronics



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Device Modification/Defect Generation

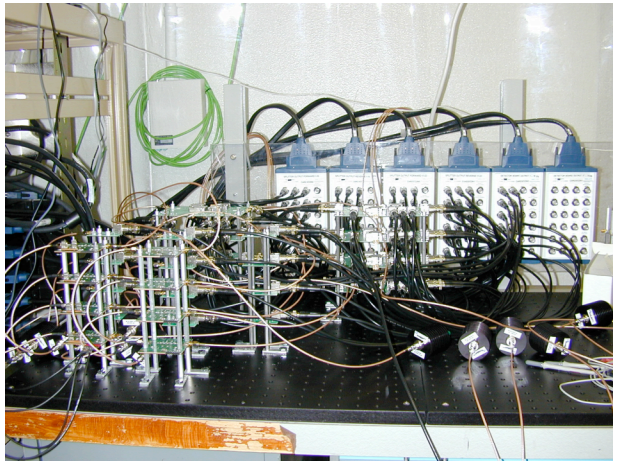
- Electrical stress (DC and RF)
- Mechanical stress
- Thermal stress
- Optical stress

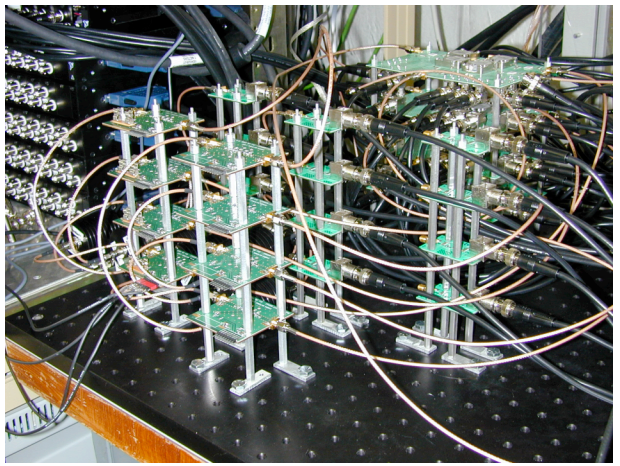
Device Modification/Defect Generation

- Electrical stress (DC and RF)
- Mechanical stress
- Thermal stress
- Optical stress

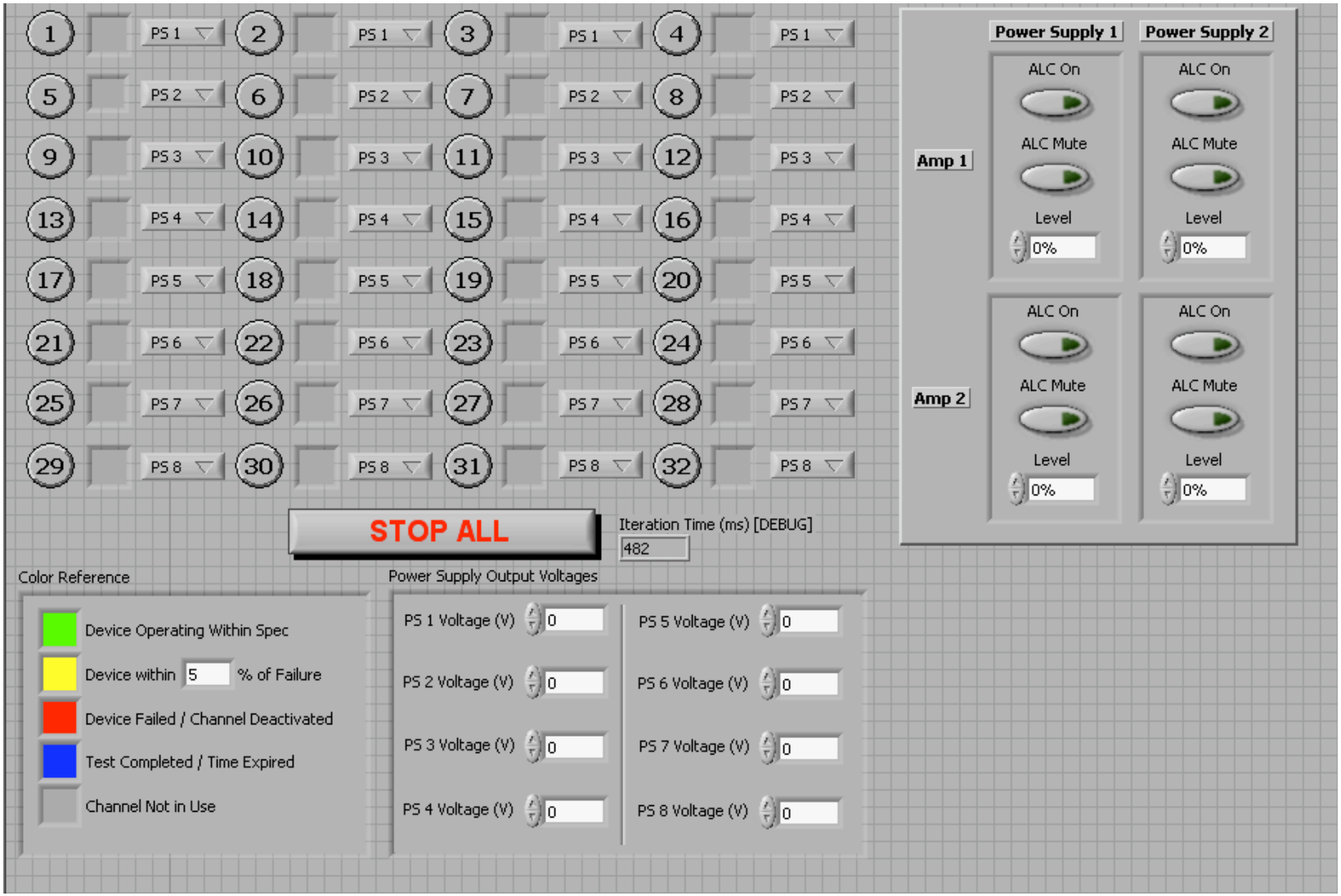
Burn-In Test System

- Supply voltage and current stressed devices to other MURI members for characterization-similar to Accel-rf but modular.
  - Provide enough samples to produce realistic statistics.
  - Currently 8 channels-expandable to 32, operational range 25-150˚C,0-60V,5W.
  - Will integrate IR camera and illumination source.

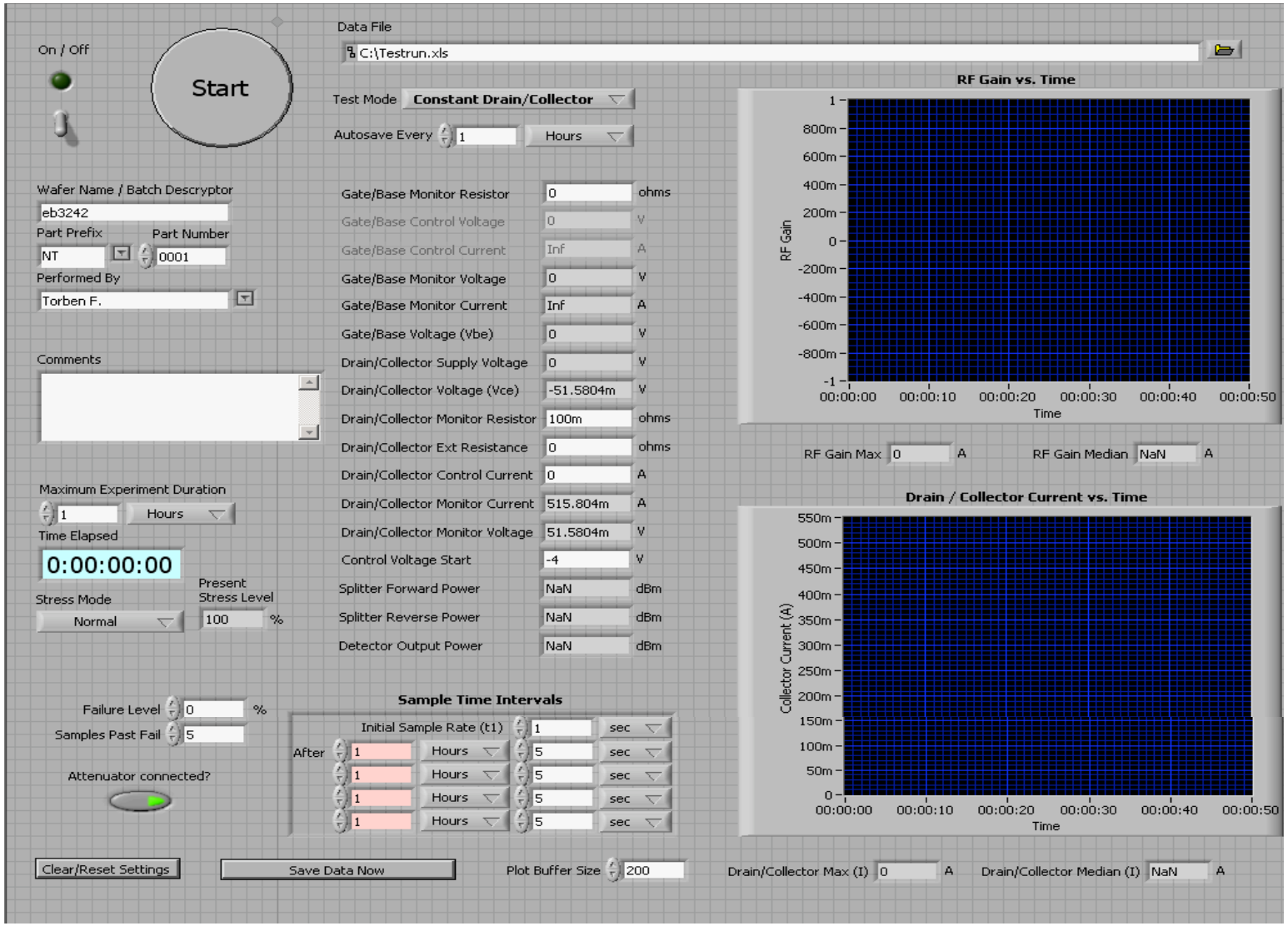




Master System Monitor



Single Device Monitor



Device Modification/Defect Generation

- Electrical stress (DC and RF)
- Mechanical stress
- Thermal stress
- Optical stress

Sources of Mechanical Stress

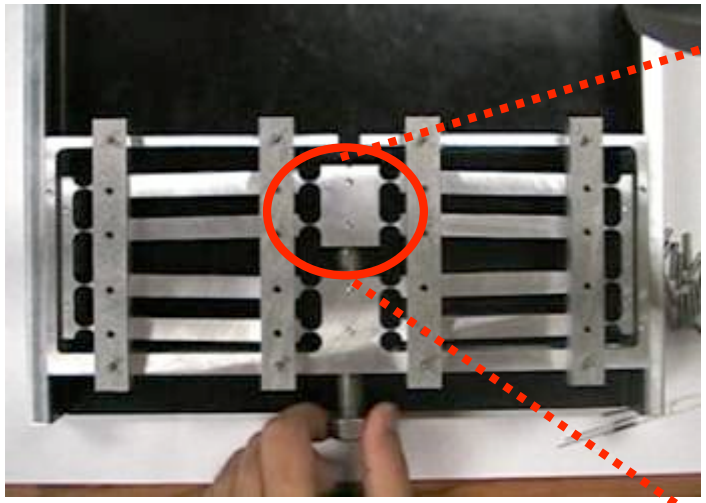
- Fabrication process-induced mechanical stress
  - Lattice mismatch
  - CVD thin film residual stress
  - Dopant-incorporation
- Bias-induced stress via inverse piezoelectric effect
- Package/Encapsulation/Operational stress
  - Thermal coefficient of expansion mismatch
  - Intermetallic growth

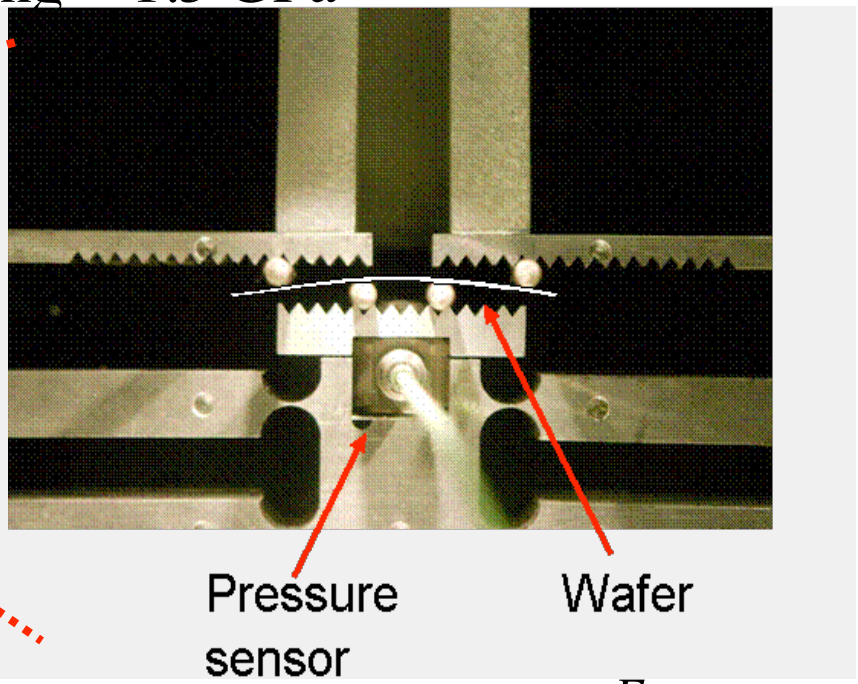
>> Varying process stress may change device <<

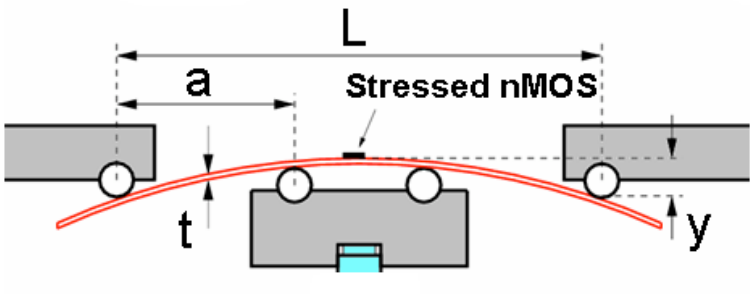
➢ Controlled applied mechanical stress

Externally Applied Mechanical Stress

- Flexure based four point bending jig
  - Highest to date wafer bending ~ 1.5 GPa



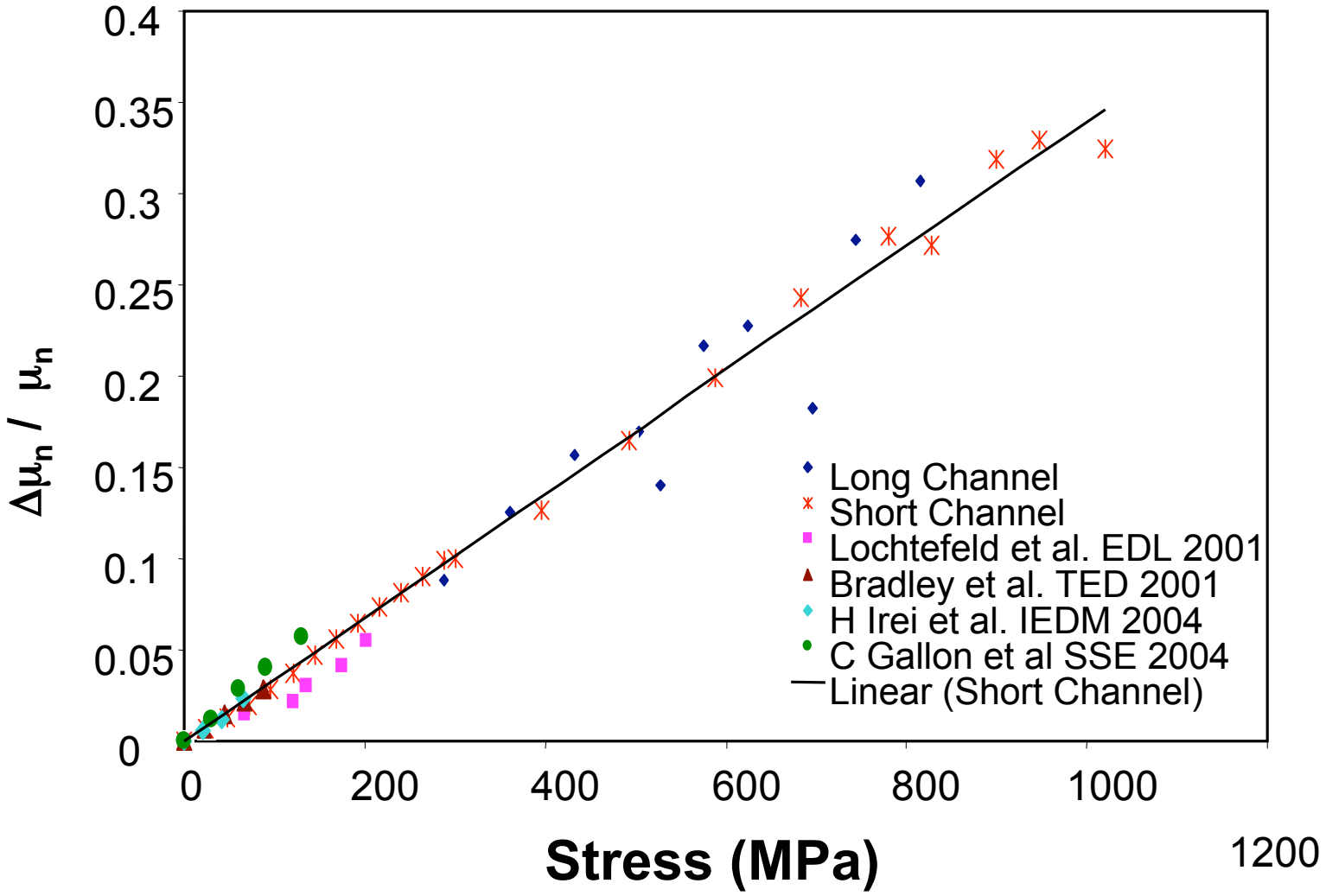




$$\sigma = \frac{Eyt}{2a\left(\frac{L}{2} - \frac{2a}{3}\right)}$$

Ref: S. Suthram et al., "Piezoresistance Coefficients of (100) Silicon nMOSFETs Measured at Low and High (~1.5GPa) Channel Stress", IEEE Electron. Dev. Lett., Vol. 28, pp. 58 – 61, January 2007

Electron Mobility Enhancement in Si nMOSFET

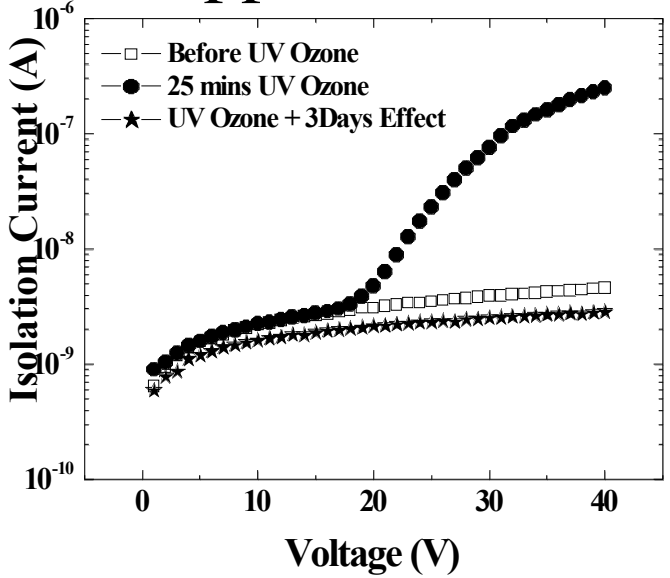


Device Modification/Defect Generation

- Electrical stress (DC and RF)
- Mechanical stress
- Thermal stress
  - Active heating from electrical stress
  - Calibration via passive heating
- Optical stress
  - UV stress of materials

UV Stress

- Excitation of trapped carriers in material layers



  - Initial dark isolation current baseline
  - UV stress-induced increase in isolation current
  - Recovery time for post dark isolation current
    - Go/No-go digital test
    - Integrate with other stressors to investigate defect generation/relaxation and capture/emission

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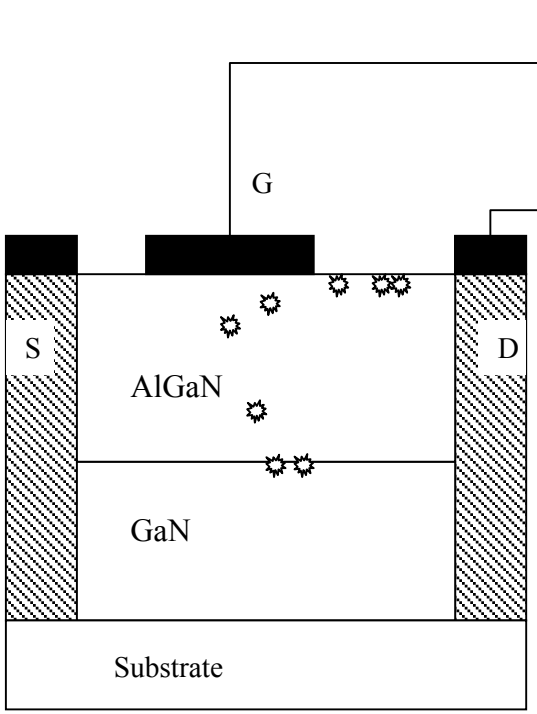
Characterization

- On-state and off-state currents
- Stress and recovery transients
- Noise characterization
- IR and uRaman

Noise Characterization

- Noise signatures
  - Only due to defects that interact directly with charge carriers
- Technique
  - Employs standard devices
  - Measures drain and gate current PSD
    - Frequency dependent component at low frequencies
    - Frequency independent

Experimental Noise Setup for an AlGaN/GaN HEMT



Low Noise Amplifiers

Dual channel spectrum analyzer for cross and autospectral density measurements

- Possible locations of hot electron or reverse piezo electric induced traps generating noise

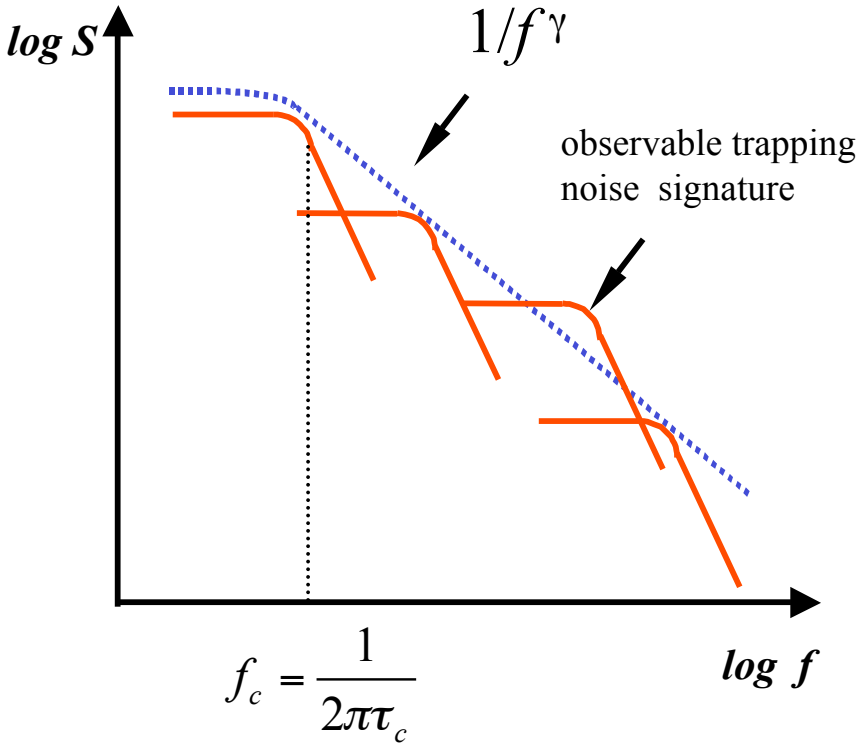
Defect Noise Spectroscopy

Advantages of Noise Spectroscopy

- Only defects that actually affect charge transport are probed in actual devices and under realistic bias conditions.
- Microscopic noise signatures provide early warning of macroscopic breakdown.

Data Extraction

- Measured low frequency noise spectra typically consist of a superposition of trapping noise components
- From S vs. V_D data, the lateral position of defects can be determined
- From S vs. V_G data the vertical position in the gate-stack region can be determined
- From S vs. T data, the defect activation energy can be extracted

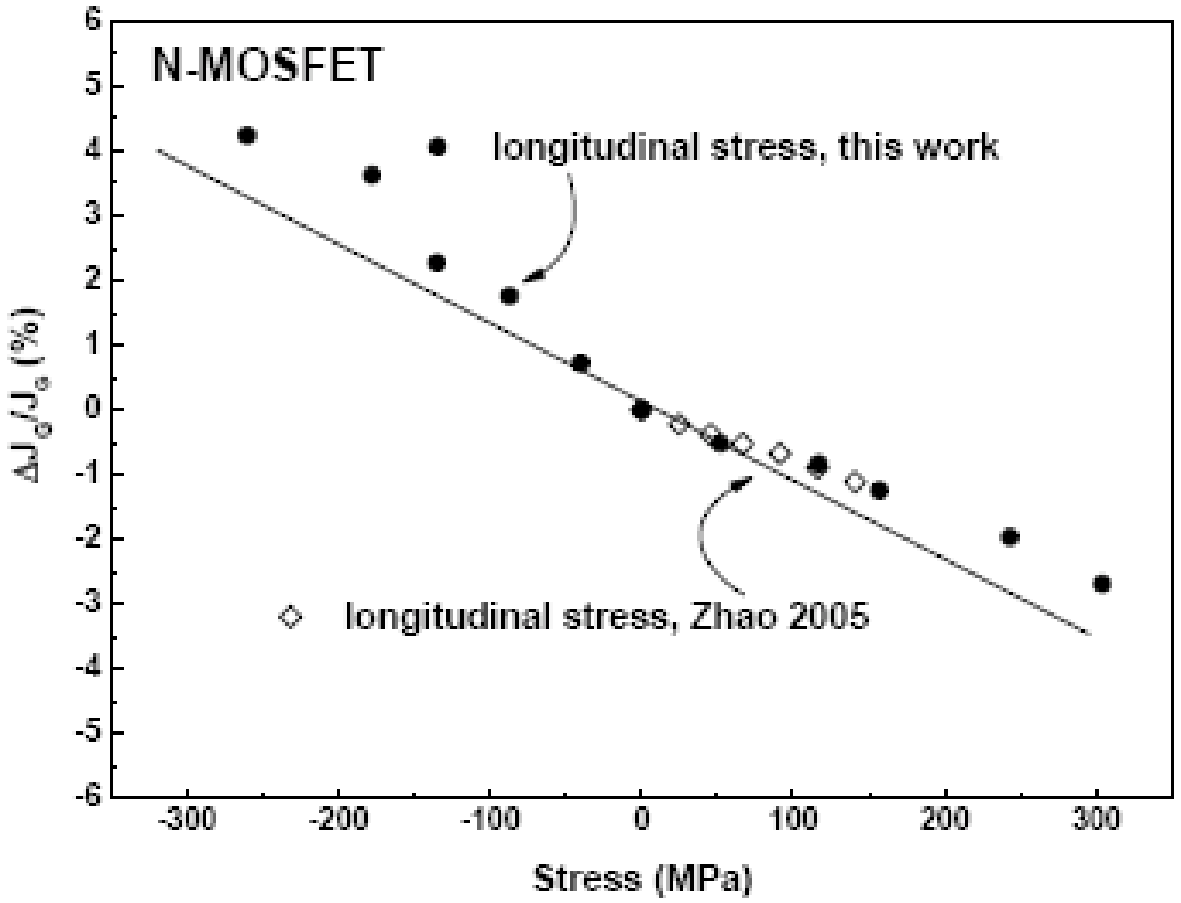


Related Results and Preliminary Models

- Related results
  - Stress dependence
    - Si MOSFET gate leakage currents
    - HfSiO, HfSiON dielectric constant
    - Time-dependent dielectric breakdown (TDDB)
- Forward/Inverse piezoelectric effect

Strain Altered Gate Leakage of Si n-MOSFET

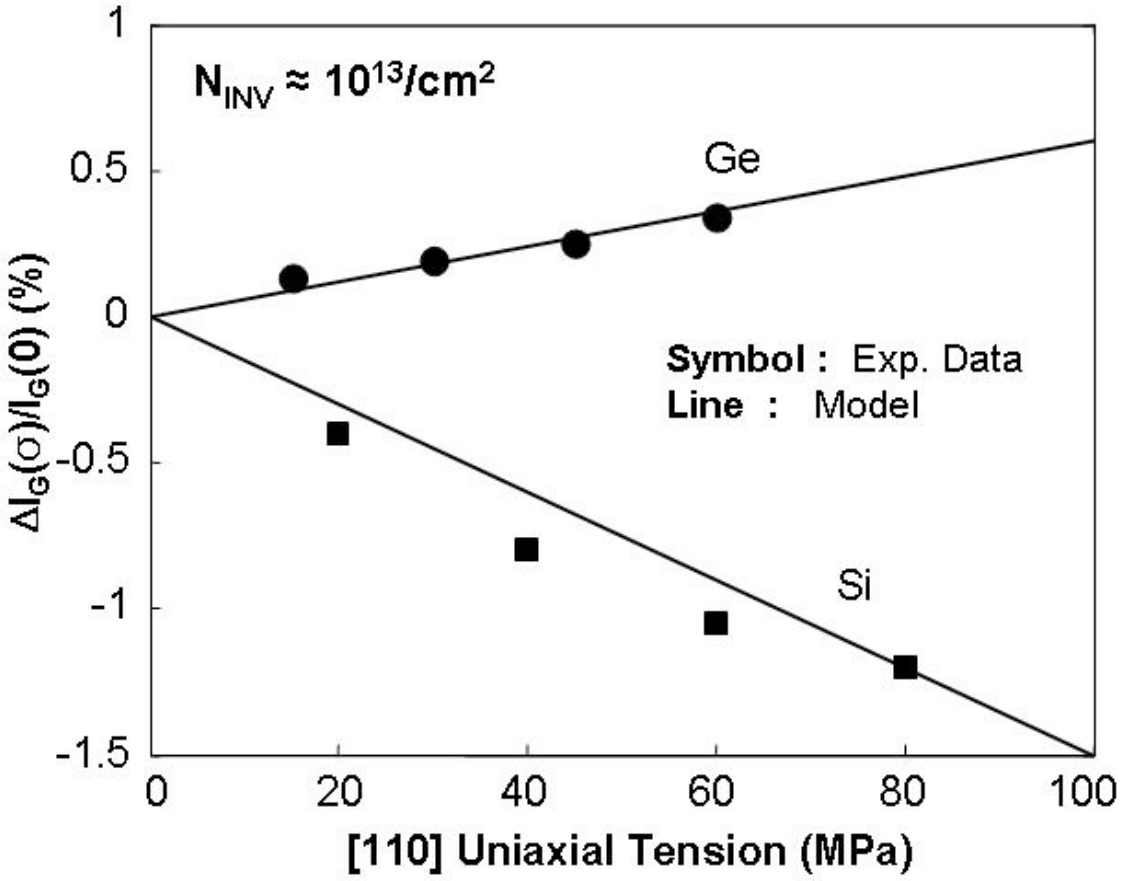
- Gate leakage increases/decreases with uniaxial longitudinal compression/tension along [110] direction



X. Yang et al. 2007 Electron Device and and Semiconductor Technology

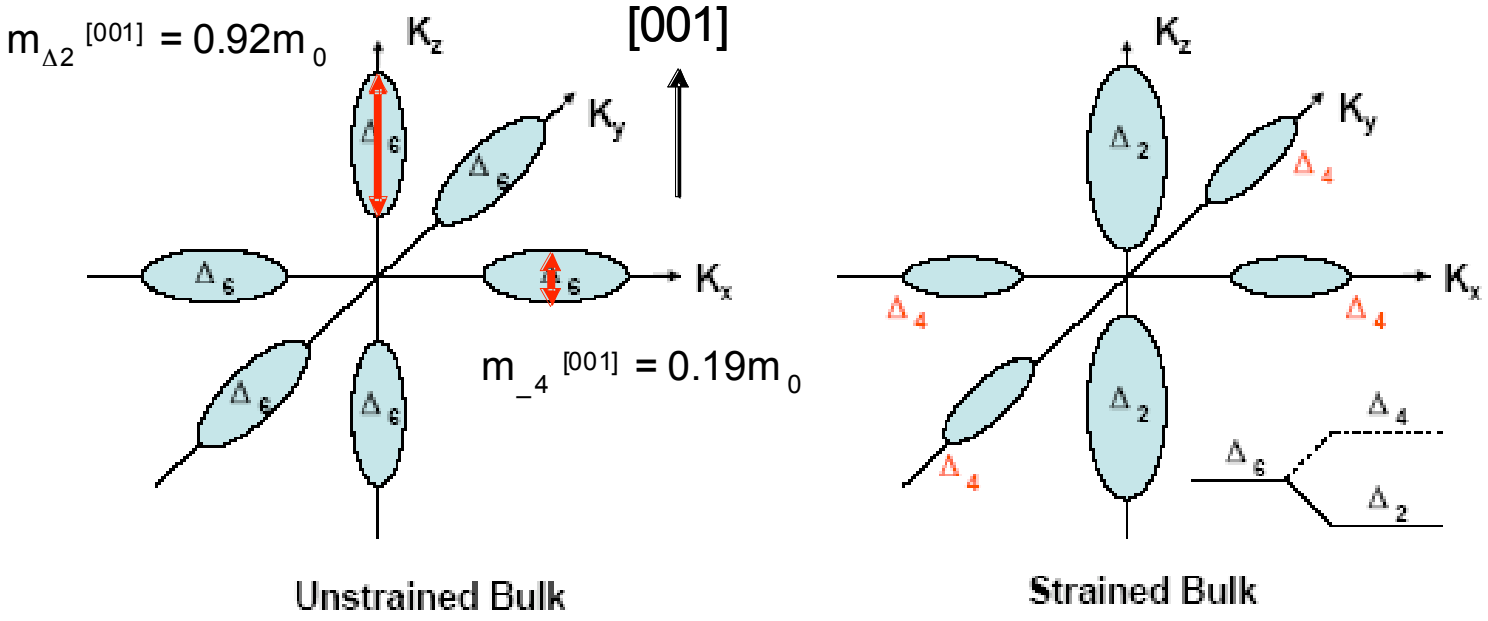
Strain-Altered Gate Leakage of Ge & Si n-MOSFETs

- I_G (Ge) increases, while I_G (Si) decreases with [110] uniaxial tension



Y.S. Choi et al. JAP 2007

Conduction Band Edge of Si

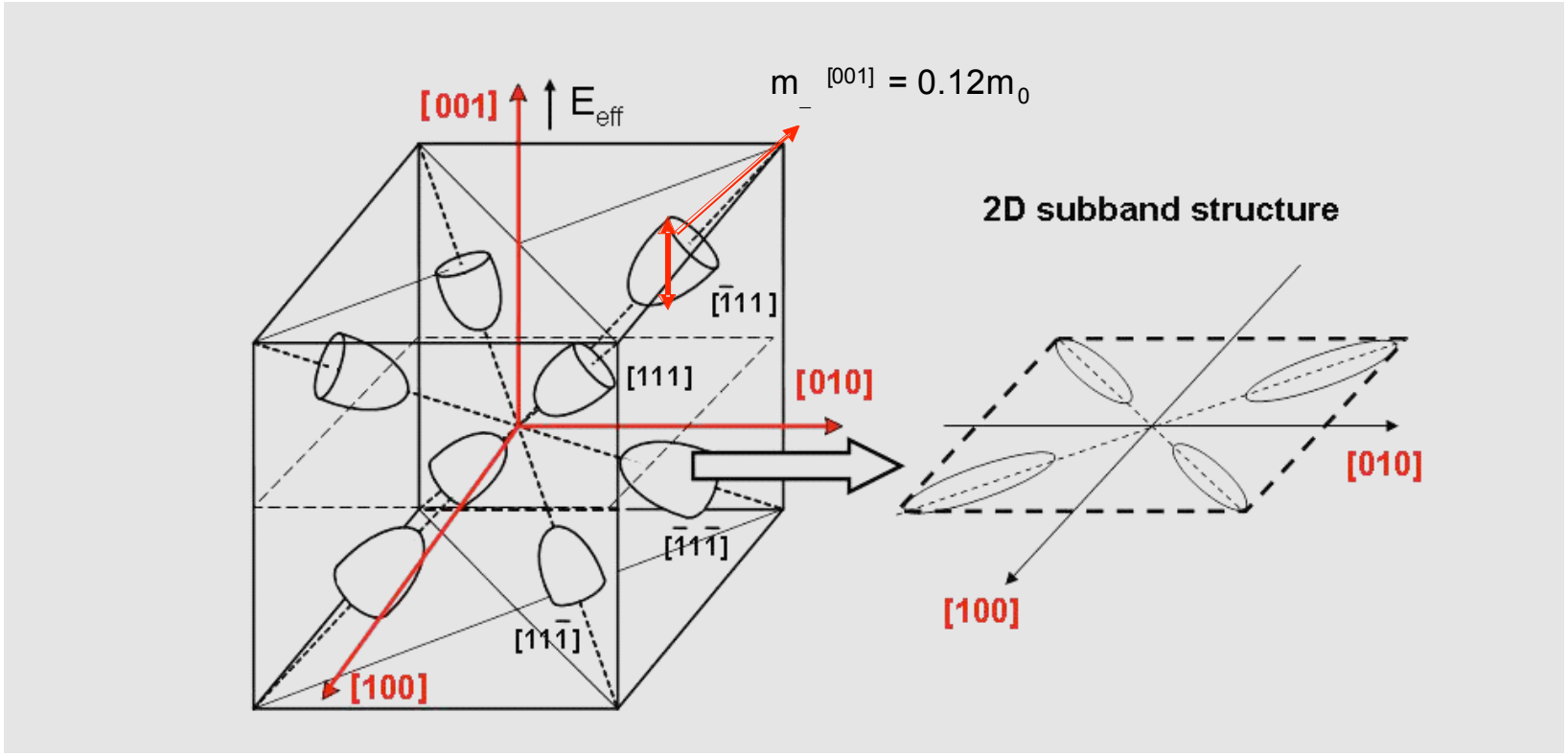


X. Yang et al. 2007 Electron Device and and Semiconductor Technology

- *Conduction-band constant energy ellipsoids are centered along the Δ axis*
- *The major axis of six ellipsoids are along [100] direction.*

[110] Uniaxial Stress removes degeneracy and cause subband splitting

Conduction Band Edge of Ge



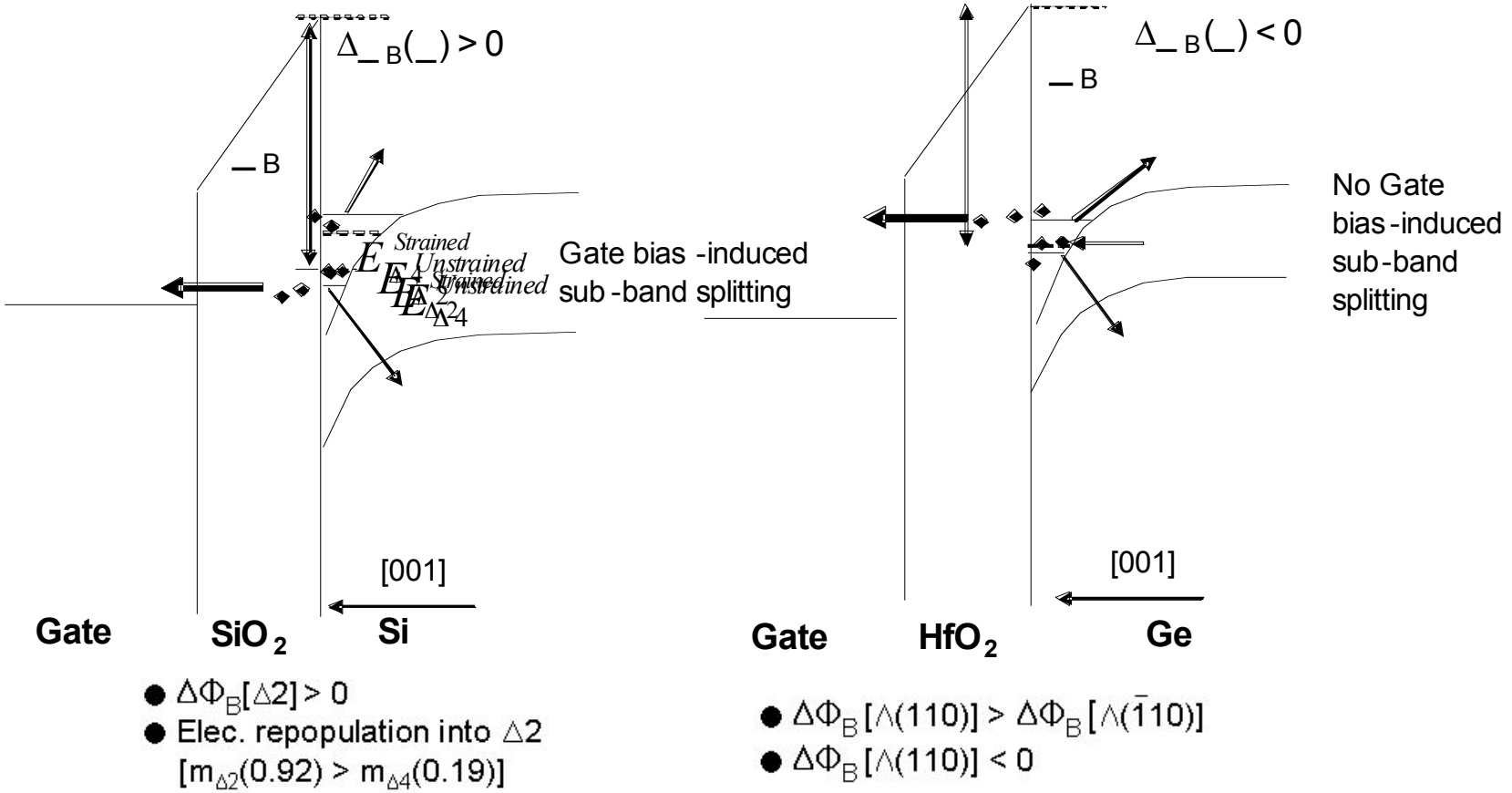
- *Conduction-band constant energy ellipsoids are centered at the L point*
- *The major axis of eight half ellipsoids are along Λ or [111] direction.*

Only one out-of-plane effective mass ($0.12m_0$)

Y.S. Choi et al. JAP 2007

Band Diagrams of Stressed Si & Ge n-MOSFETs

Tensile stress along [110] direction



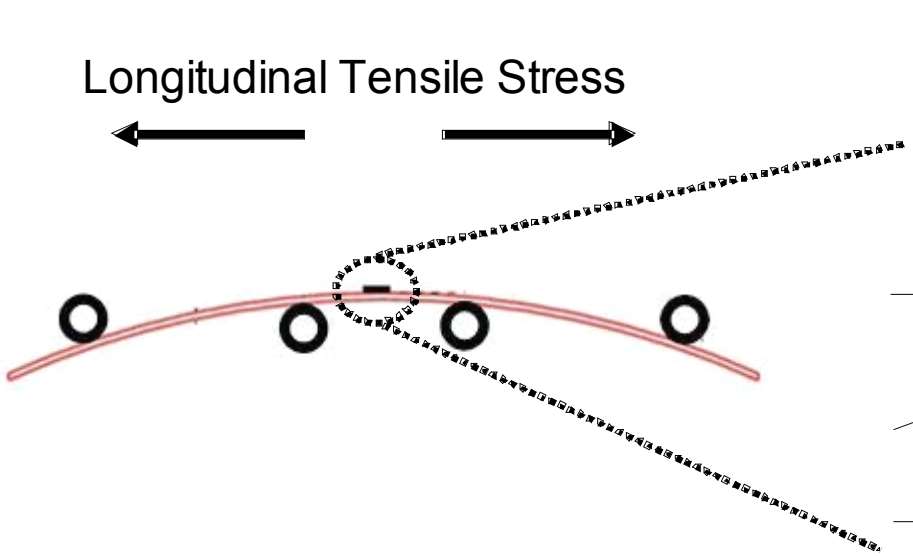
- $\Delta\Phi_B[\Delta 2] > 0$
- Elec. repopulation into $\Delta 2$ $[m_{\Delta 2}(0.92) > m_{\Delta 4}(0.19)]$

- $\Delta\Phi_B[\wedge(110)] > \Delta\Phi_B[\wedge(\bar{1}10)]$
- $\Delta\Phi_B[\wedge(110)] < 0$

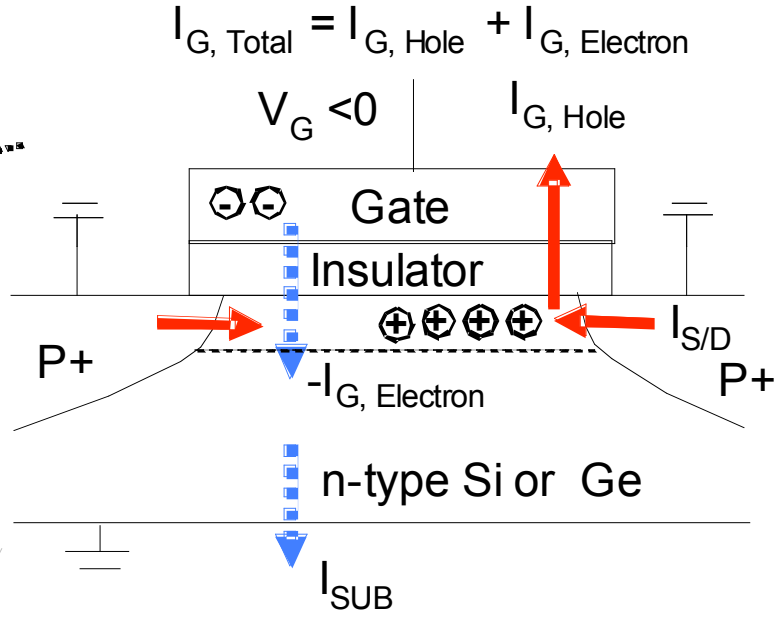
m increases due to repopulation => I_G decreases*

Φ_B lowers due to band shift & splitting => I_G increases

4-point wafer bending + Carrier Separation



4 point wafer bending

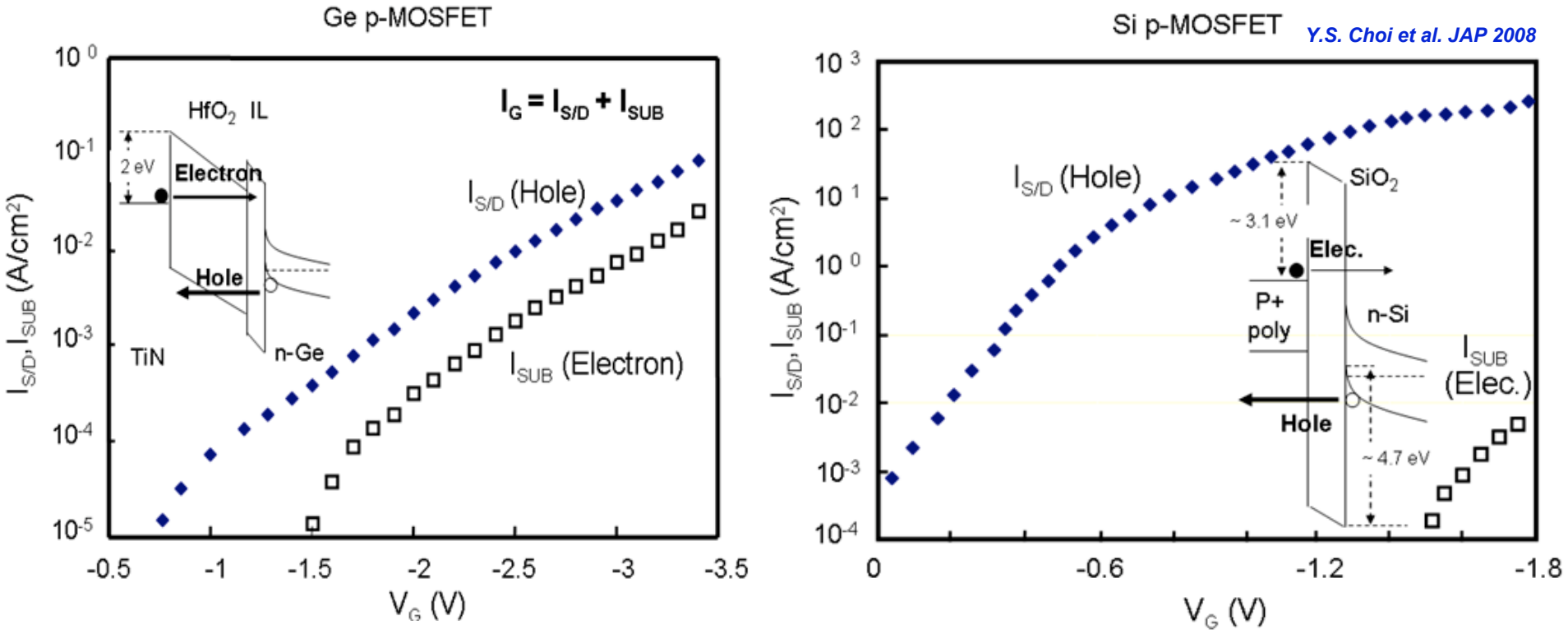


Carrier separation method

Y.S. Choi et al. JAP 2008

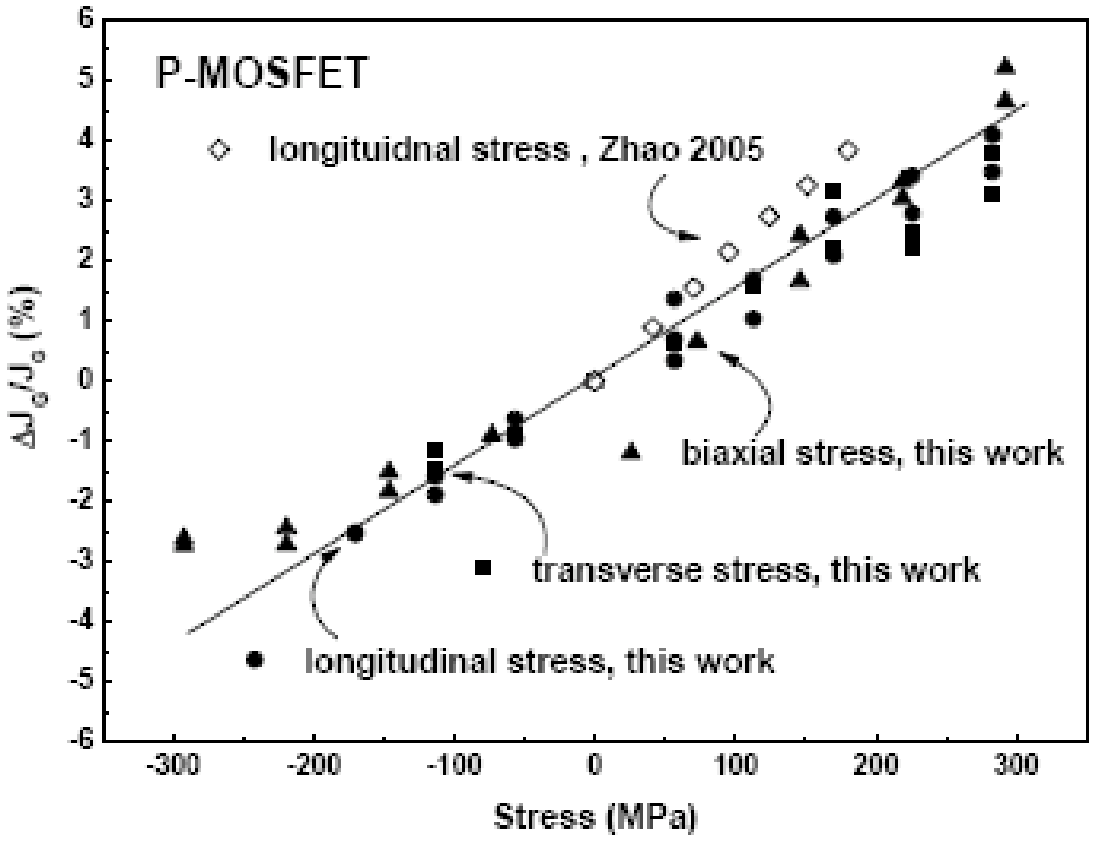
Strain effect on each gate tunneling carrier (electron & hole) can be monitored!!

Carrier Separation of Si & Ge p-MOSFETs



- *Hole tunneling from sub. is dominant for both Si & Ge p-MOSFETs*
- *I_{SUB}/I_G(Ge) > I_{SUB}/I_G(Si) due to metal gate in Ge device*

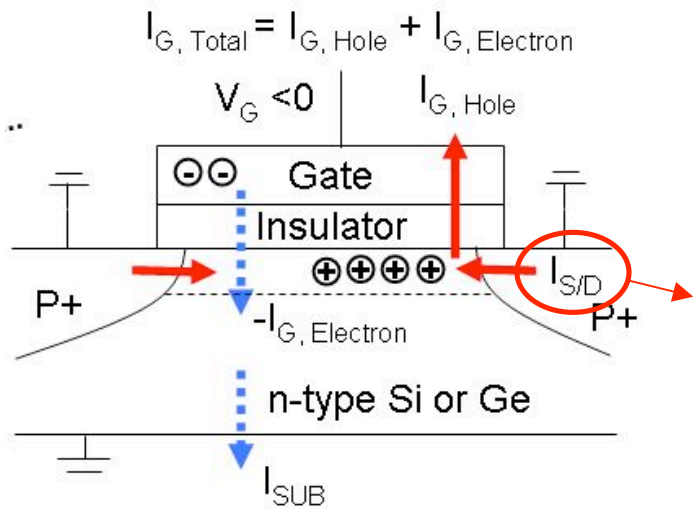
Strain Altered Gate Leakage of Si p-MOSFET

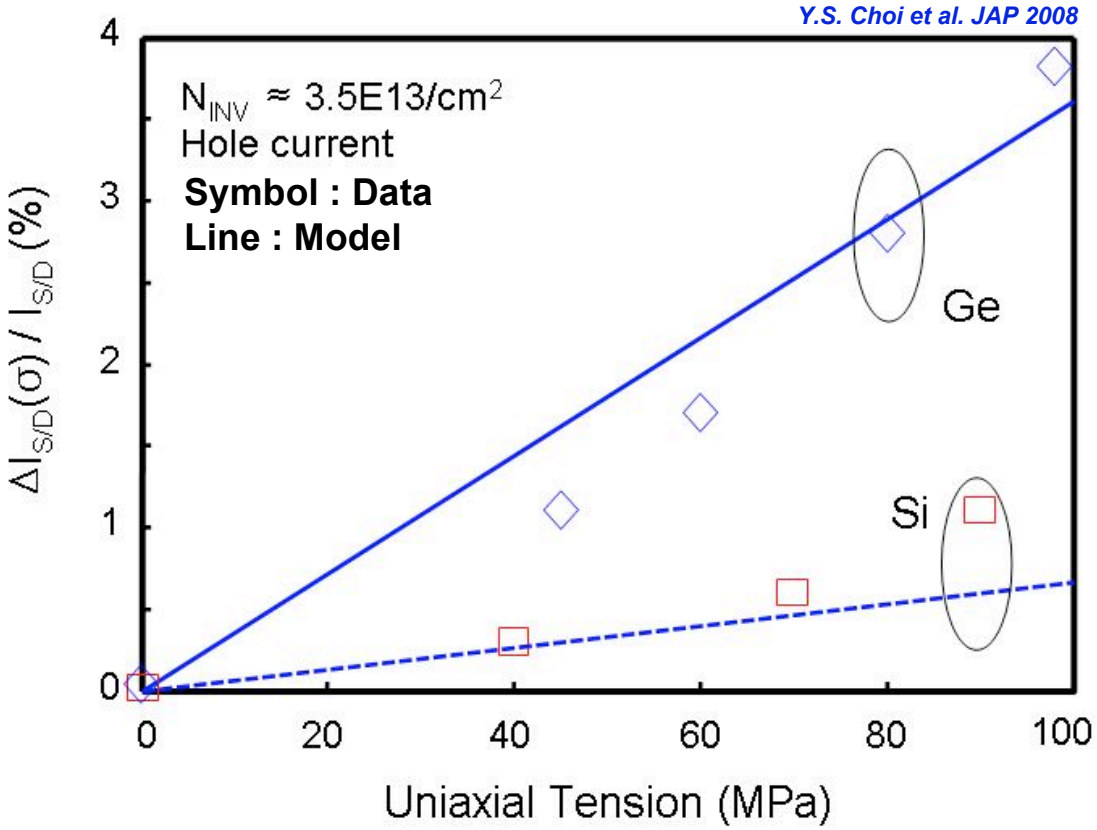


X. Yang et al. 2007 Electron Device and and Semiconductor Technology

J_G decreases/increases with uniaxial longitudinal compression/tension along [110] direction

Strain-Altered Gate Leakage Ge & Si p-MOSFETs from Inversion Layer



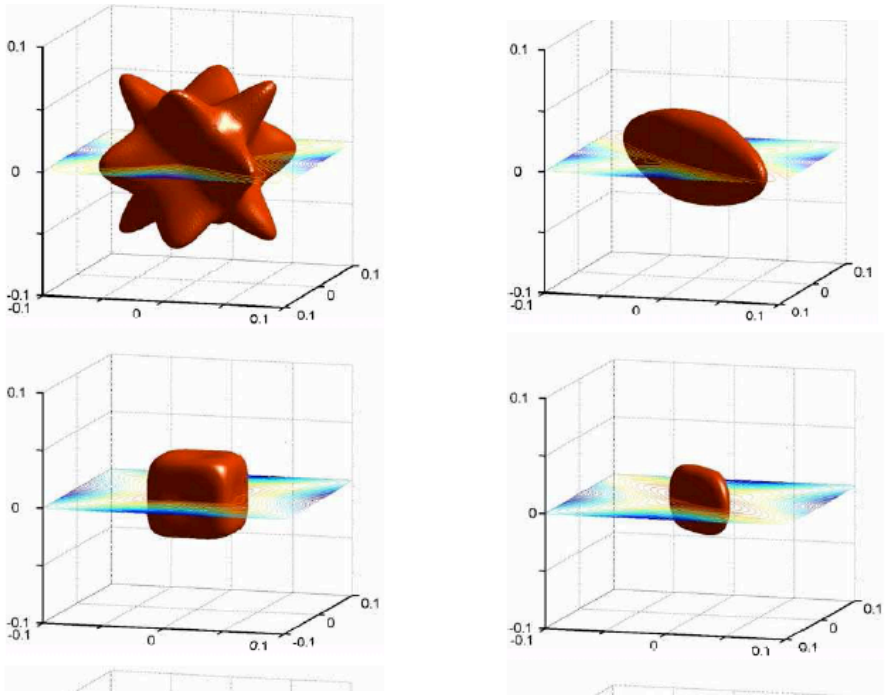


$$\Delta I_{S/D} / I_{S/D}^{Ge}(\sigma) > \Delta I_{S/D} / I_{S/D}^{Si}(\sigma)$$

Same Physics for Holes in Si and Ge

Si

Ge



Unstressed

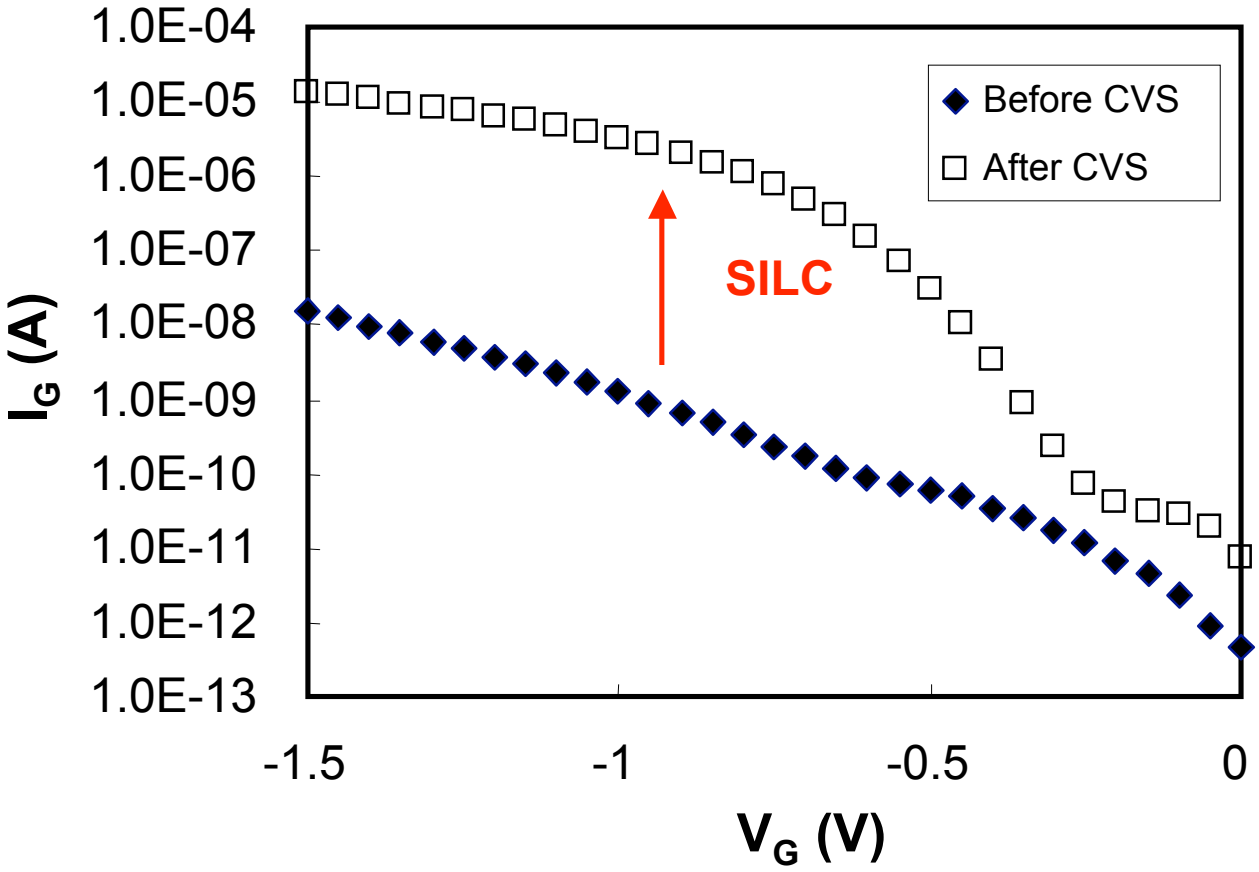
1GPa Uniaxial compression

Guangyu Sun
Ph. D Dissertation 2007

- *Same valence band edge for Si & Ge (Γ-point)*
- *Under applied stress, valence band edge shifts & splits with same manner, but based on different deformation potential constants of Si & Ge*
- *Different strain-altered effective mass & subband splitting*

Constant Voltage Stressing (CVS)

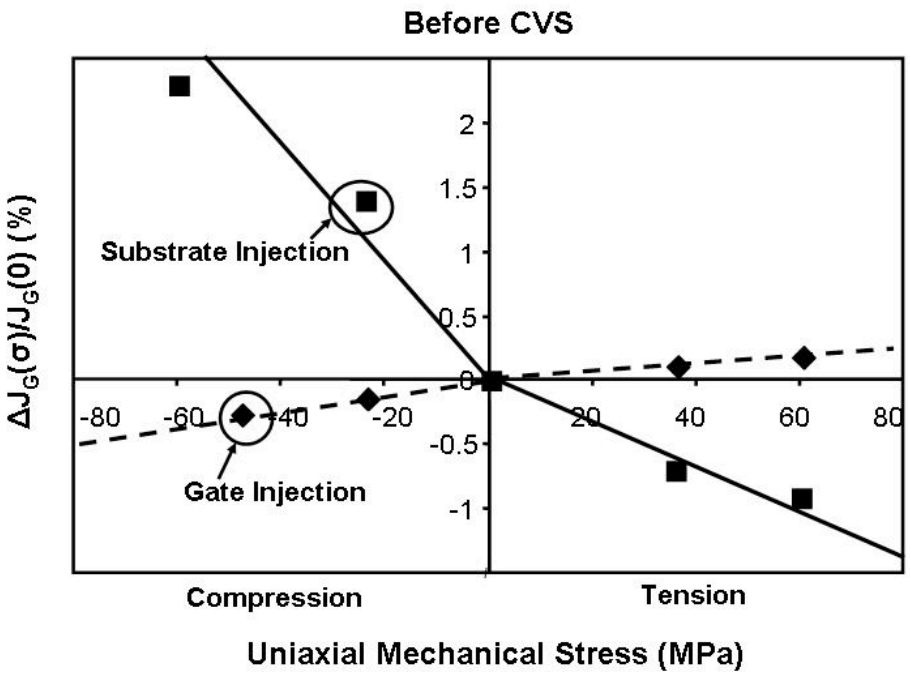
SILC = Stress Induced Leakage Current

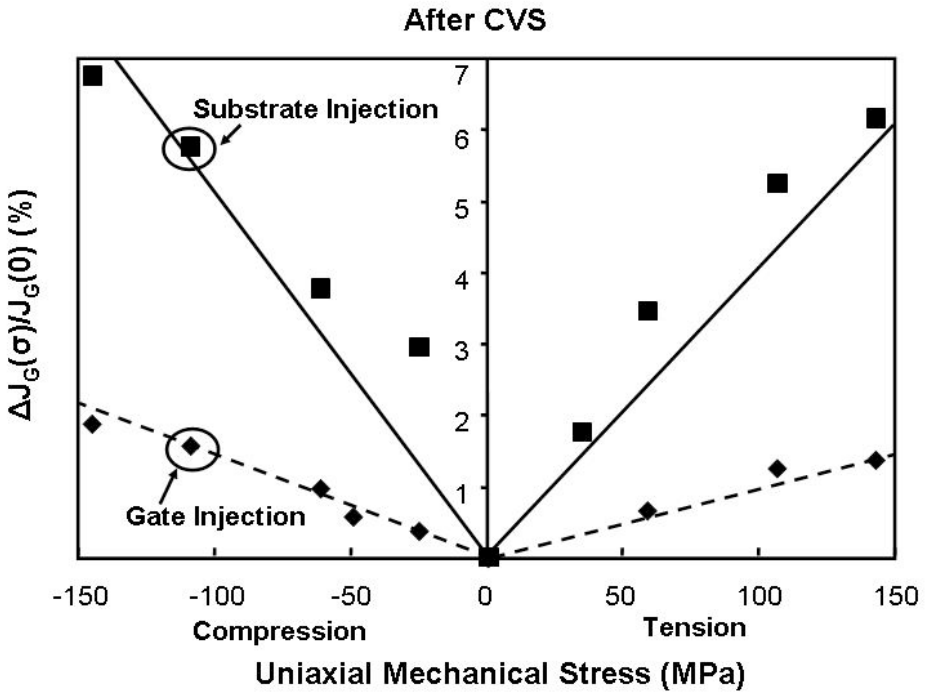


- Stressing Condition = -4 V for 50 Sec
- Sample Structure = TaN/2.5 nm SiO_2/p-Si
- Area of Sample = 10^5 μm^2

High-field stress (Fowler-Nordheim stress) generates electron traps in the SiO_2/Si interface that facilitate trap-assisted tunneling

Strain Altered Gate Leakage Before and After CVS

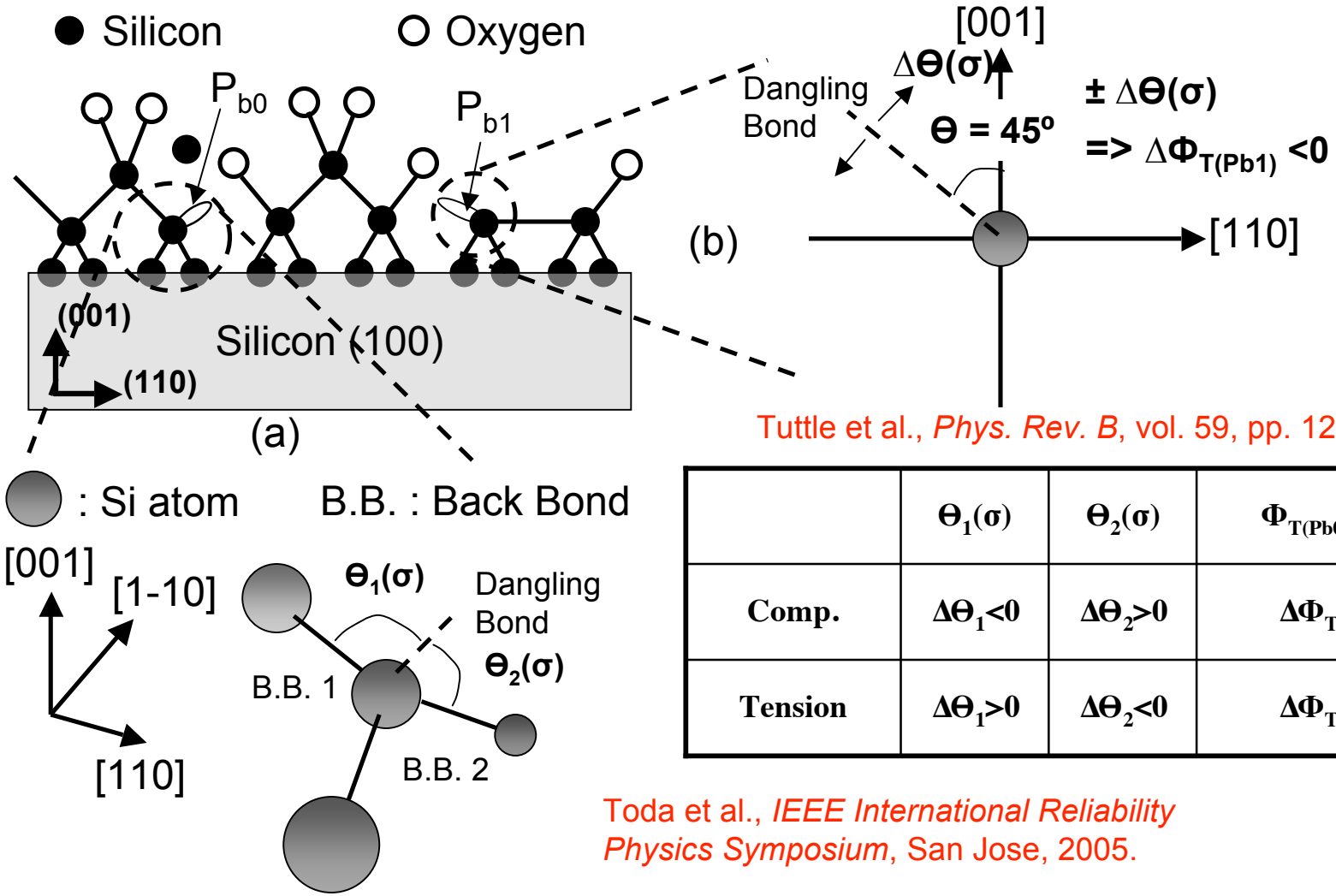




Before CVS=> An opposing uniaxial stress dependence between Gate and Sub. Injections

After CVS=> Both gate and sub. Injections increase with uniaxial [110] stress

[110] Uniaxial Stress vs Interface Trap E_A



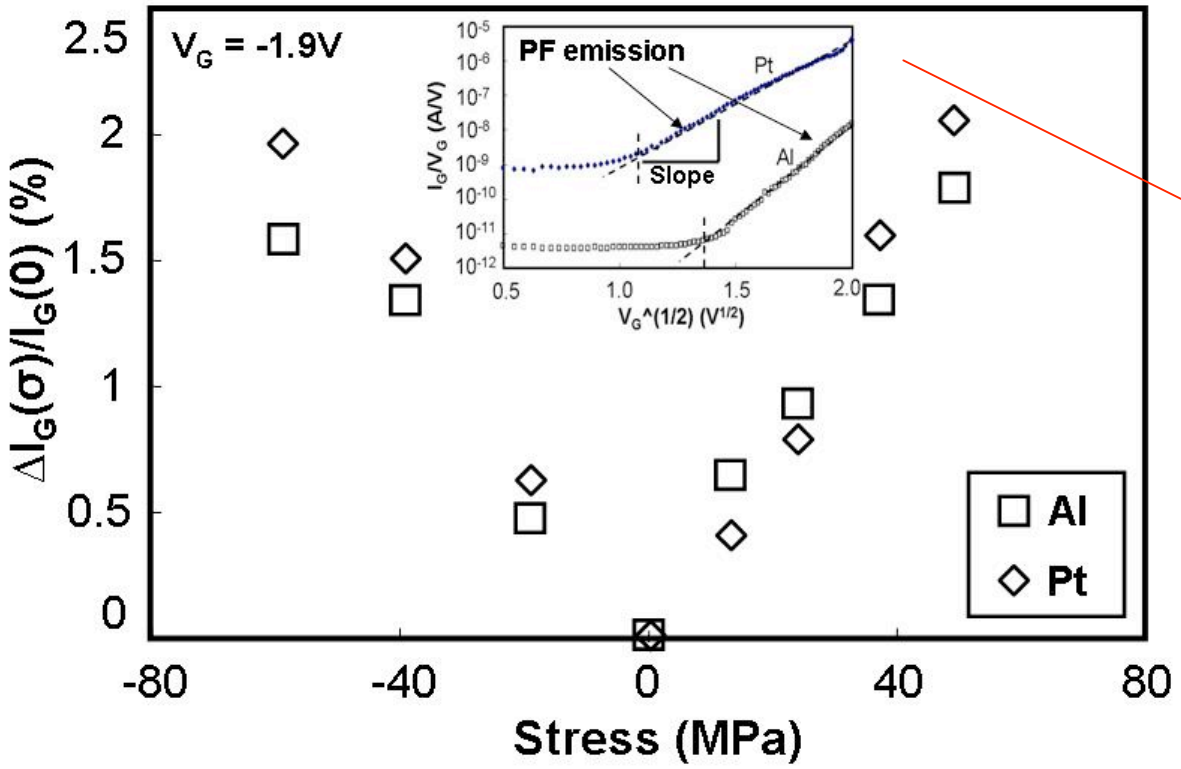
Tuttle et al., *Phys. Rev. B*, vol. 59, pp. 12884(1999)

	$\Theta_1(\sigma)$	$\Theta_2(\sigma)$	$\Phi_{T(Pb0)}(\sigma)$
Comp.	$\Delta\Theta_1<0$	$\Delta\Theta_2>0$	$\Delta\Phi_T<0$
Tension	$\Delta\Theta_1>0$	$\Delta\Theta_2<0$	$\Delta\Phi_T<0$

Toda et al., *IEEE International Reliability Physics Symposium*, San Jose, 2005.

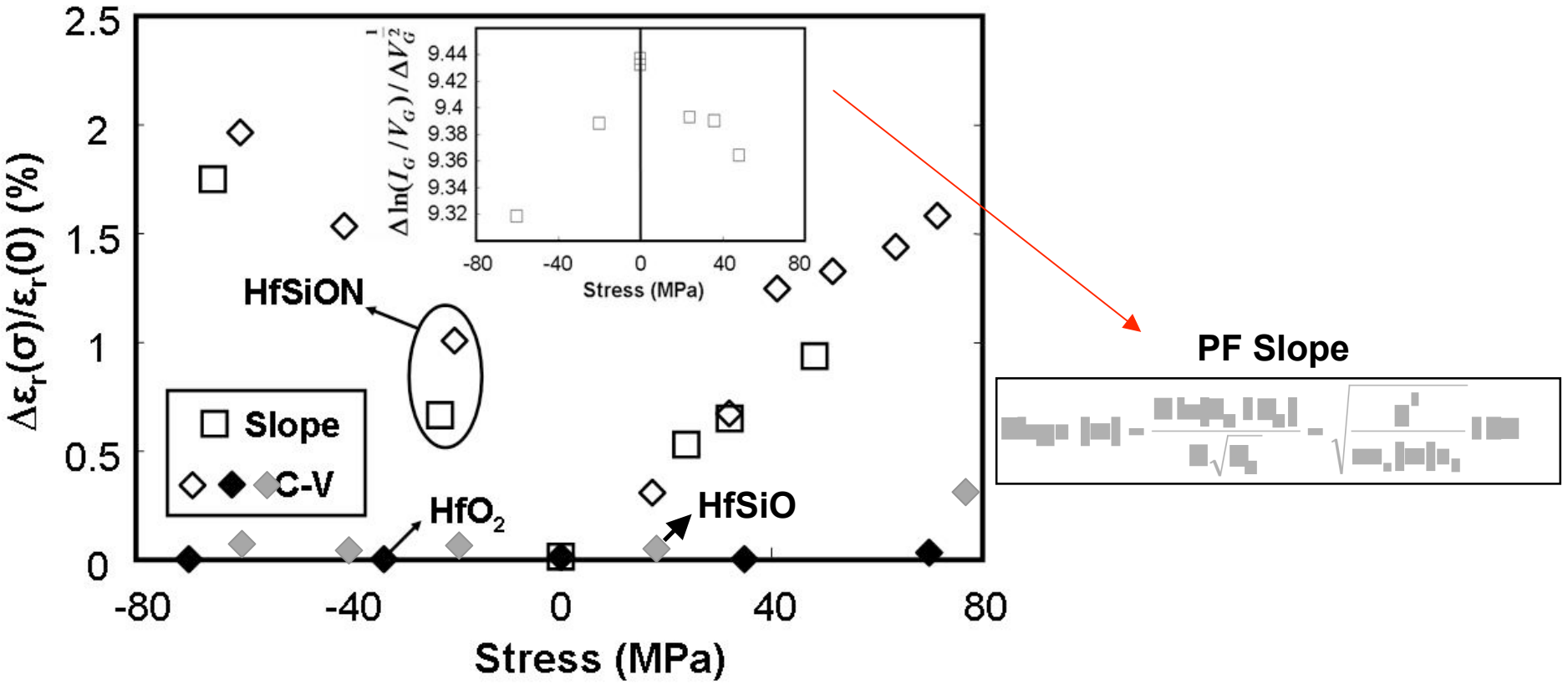
[110] tensile & compressive stresses decreases trap activation energy

Stress Effect on Gate Leakage in HfSiON



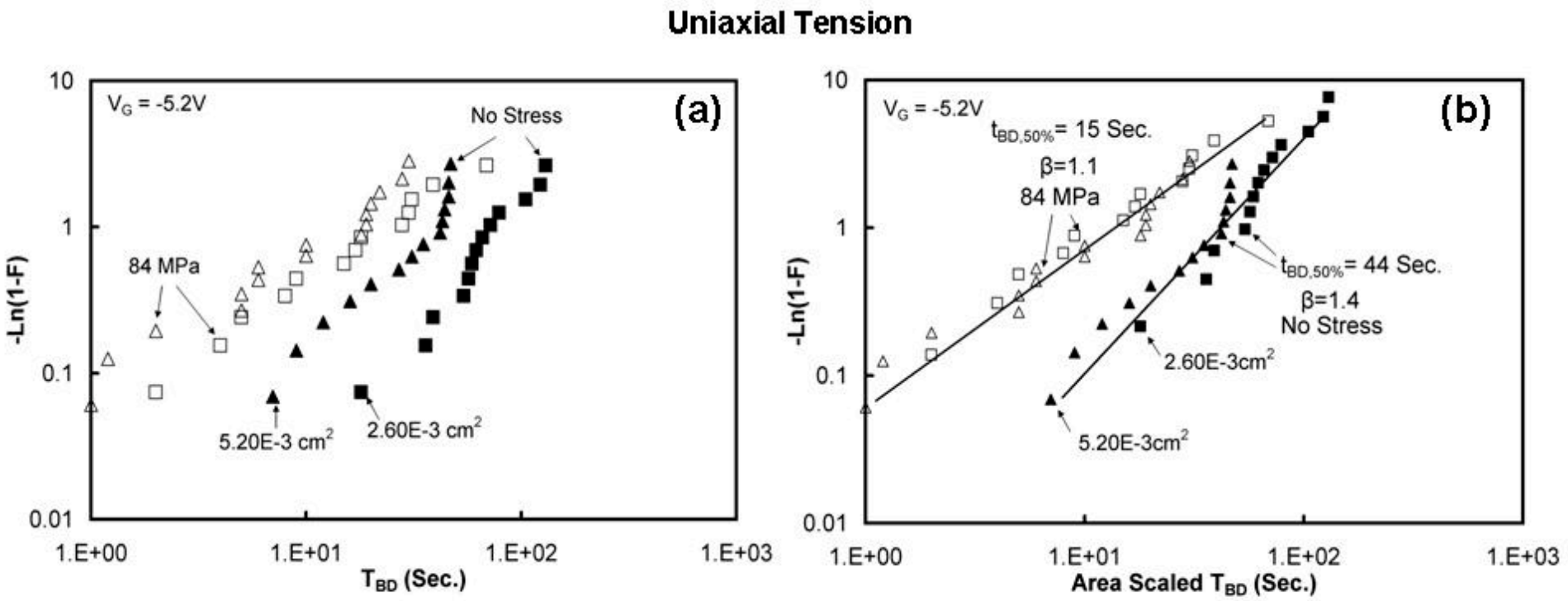
- *PF Emission => Trap-Assisted Gate Tunneling*
- *I_G increases with both [110] uniaxial tension & compression*

Stress Effect on Dielectric Constant of HfSiON



- *ε_r of HfSiON increases with both tension and compression*
- *Nitrogen incorporation ~ Strain effect on ε_r*

Stress Effect on TDDB



- *TDDB on Al-gate HfSiON on p-Si MOS capacitor decreases with tensile stress*

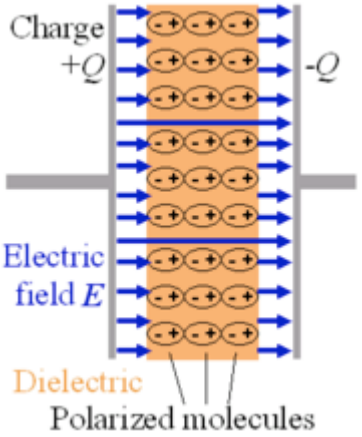
Related Results and Preliminary Models

- Related results
  - Stress dependence
    - Si MOSFET gate leakage currents
    - HfSiO, HfSiON dielectric constant
    - Time-dependent dielectric breakdown (TDDB)
- Forward/Inverse piezoelectric effect

Piezoelectric Effect

Piezoelectricity: Effect of nonvanishing electric field (polarization) induced by strain.

The fundamental cause of peizoelectricity: ***lack of a center of inversion***.
No piezoelectric effect in elementary semiconductors.



Example of semiconductors having piezoelectricity
GaAs: zinc-blende
GaN: wurtzite

GaAs: Only $e_{44} \neq 0$

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & e_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & e_{44} \end{pmatrix} \begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{pmatrix}$$

Polarization | Piezoelectric tensor | Strain

GaN: $e_{13} \neq 0$, $e_{33} \neq 0$, and $e_{15} \neq 0$

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{pmatrix}$$

Inverse Piezoelectric Effect: Strain induced by applied electric field.

Modeling Cumulative Effect of Stress on Reliability

- Open questions
  - Relative contribution of fixed/variable mechanical stressors
    - Fabrication
    - Bias/ inverse piezoelectric effect
    - Package/encapsulation/thermal mismatch
  - Bond configuration change
  - Model as electrical-mechanical-temperature-optical stress dependent generation cross-section?
  - Incorporation into FLOOPS reliability simulations
  - Characterization/modeling/simulation feedback loop
  - ???